

# Weakly nonlinear stochastic CGL equations.

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*Dedicated to Claude Bardos on his 70-th birthday*

## Abstract

We consider the linear Schrödinger equation under periodic boundary condition, driven by a random force and damped by a quasilinear damping:

$$\frac{d}{dt}u + i(-\Delta + V(x))u = \nu \left( \Delta u - \gamma_R |u|^{2p}u - i\gamma_I |u|^{2q}u \right) + \sqrt{\nu} \eta(t, x). \quad (*)$$

The force  $\eta$  is white in time and smooth in  $x$ . We are concerned with the limiting, as  $\nu \rightarrow 0$ , behaviour of its solutions on long time-intervals  $0 \leq t \leq \nu^{-1}T$ , and with behaviour of these solutions under the double limit  $t \rightarrow \infty$  and  $\nu \rightarrow 0$ . We show that these two limiting behaviours may be described in terms of solutions for the *system of effective equations for* (\*) which is a well posed semilinear stochastic heat equation with a non-local nonlinearity and a smooth additive noise, written in Fourier coefficients. The effective equations do not depend on the Hamiltonian part of the perturbation  $-i\gamma_I |u|^{2q}u$  (but depend on the dissipative part  $-\gamma_R |u|^{2p}u$ ). If  $p$  is an integer, they may be written explicitly.

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## 0 Introduction

In [KP08, Kuk10] we have considered the KdV equation on a circle, perturbed by a random force and a viscous damping. There we suggested auxiliary *effective equations* which are well posed and describe long-time behaviour of solutions for the perturbed KdV through a kind of averaging.

In this work we apply the method of [KP08, Kuk10] to a weakly nonlinear situation when the unperturbed equation is not an integrable nonlinear PDE (e.g. KdV), but a linear Hamiltonian PDE with a generic spectrum. Since analytic properties of the latter are easier and better understood than those of the former, in the weakly nonlinear situation we understand better properties of the effective system and its relation with the original equation. Accordingly we can go further in analysis of long time behaviour of solutions.

More precisely, we are concerned with  $\nu$ -small dissipative stochastic perturbations of the space-periodic linear Schrödinger equation

$$\frac{d}{dt}u + i(-\Delta u + V(x))u = 0, \quad x \in \mathbb{T}^d, \quad (0.1)$$

i.e. with equations

$$\frac{d}{dt}u + iAu = \nu \left( \Delta u - \gamma_R f_p(|u|^2)u - i\gamma_I f_q(|u|^2)u \right) + \sqrt{\nu} \eta(t, x), \quad x \in \mathbb{T}^d, \quad (0.2)$$

where  $\eta(t, x) = \frac{d}{dt} \sum_{j=1}^{\infty} b_j \beta_j(t) e_j(x)$ . Here  $Au = A_V u = -\Delta u + V(x)u$  and the potential  $V(x) \geq 1$  is sufficiently smooth; the real numbers  $p, q$  are non-negative, the functions  $f_p(r)$  and  $f_q(r)$  are the monomials  $|r|^p$  and  $|r|^q$ , smoothed out near zero, and the constants  $\gamma_R, \gamma_I$  satisfy

$$\gamma_R, \gamma_I \geq 0, \quad \gamma_R + \gamma_I = 1. \quad (0.3)$$

If  $\gamma_R = 0$ , then due to the usual difficulty with the zero-mode of the solution  $u$ , the term  $\Delta u$  in the r.h.s. should be modified to  $\Delta - u$ . The functions  $\{e_j(x), j \geq 1\}$  in the definition of the random force form the real trigonometric base of  $L_2(\mathbb{T}^d)$ , the real numbers  $b_j$  decay sufficiently fast to zero when  $j$  grows, and  $\{\beta_j(t), j \geq 1\}$ , are the standard complex Wiener processes. So the noise  $\eta$  is white in time and sufficiently smooth in  $x$ . It is convenient to pass to the slow time  $\tau = \nu t$  and write the equation as

$$\dot{u} + \nu^{-1} i A u = \Delta u - \gamma_R f_p(|u|^2) u - i \gamma_I f_q(|u|^2) u + \eta(\tau, x), \quad (0.4)$$

where  $\dot{u} = du/d\tau$ . The equation is supplemented with the initial condition

$$u(0, x) = u_0(x). \quad (0.5)$$

It is known that under certain restrictions on  $p, q$  and  $d$  the problem (0.4), (0.5) has a unique solution  $u^\nu(\tau, x)$ ,  $\tau \geq 0$ , and eq. (0.4) has a unique stationary measure  $\mu^\nu$ . We review these results in Section 1 (there attention is given to the 1d case, while higher-dimensional equations are only briefly discussed).

Let  $\{\varphi_k, k \geq 1\}$ , and  $\{\lambda_k, k \geq 1\}$ , be the eigenfunctions and eigenvalues of  $A_V$ ,  $1 \leq \lambda_1 \leq \lambda_2 \leq \dots$ . We say that a potential  $V$  is *nonresonant* if  $\sum_{j=1}^{\infty} \lambda_j s_j \neq 0$  for every finite non-zero integer vector  $(s_1, s_2, \dots)$ . In Sections 1.4, 1.5 we show that nonresonant potentials are typical both in the sense of Baire and in the sense of measure. Assuming that  $V$  is nonresonant we are interested in two questions:

Q1. What is the limiting behaviour as  $\nu \rightarrow 0$  of solutions  $u^\nu(\tau, x)$  on long time-intervals  $0 \leq \tau \leq T$ ?

Q2. What is the limiting behaviour of the stationary measure  $\mu^\nu$  as  $\nu \rightarrow 0$ ?

For any complex function  $u(x)$ ,  $x \in \mathbb{T}^d$ , denote by  $\Psi(u) = v = (v_1, v_2, \dots)$  the complex vector of its Fourier coefficients with respect to the basis  $\{\varphi_k\}$ , i.e.  $u(x) = \sum v_j \varphi_j$ . Denote

$$I_j = \frac{1}{2} |v_j|^2, \quad \varphi_j = \text{Arg } v_j, \quad j \geq 1. \quad (0.6)$$

Then  $(I, \varphi) \in \mathbb{R}_+^\infty \times \mathbb{T}^\infty$  are the action-angles for the linear equation (0.1). The  $v$ - and  $(I, \varphi)$ -variables are convenient to study the two questions above. Writing (0.4) in the  $(I, \varphi)$ -variables we arrive at the following system:

$$\frac{d}{d\tau} I_j = \dots, \quad \frac{d}{d\tau} \varphi_j = \lambda_j + \dots, \quad (0.7)$$

where the dots stand for terms of order one (stochastic and deterministic). We have got slow/fast stochastic equations to which the principle of averaging is formally applicable (e.g., see [AKN89, LM88] for the classical deterministic averaging and [Kha68, FW98] for the stochastic averaging). Denoting  $I_j^\nu(\tau) = I_j(u^\nu(\tau))$  and averaging in  $\varphi$  the  $I$ -equations in (0.7), using the rules of the stochastic calculus [Kha68, FW98] and following the arguments in [KP08], we show in Section 2 that along sequences  $\nu_j \rightarrow 0$  we have the convergences

$$\mathcal{D}(I^{\nu_j}(\cdot)) \rightharpoonup \mathcal{D}(I^0(\cdot)), \quad (0.8)$$

where the limiting process  $I^0(\tau)$ ,  $0 \leq \tau \leq T$ , is a weak solution of the averaged  $I$ -equations. As in the KdV-case the averaged equations are singular and we do not know if their solution is unique. So we do not know if the convergence (0.8) holds as  $\nu \rightarrow 0$ . To continue the analysis we write eq. (0.4) in the  $v$ -variables

$$\dot{v}_k + i\nu^{-1} \lambda_k v_k = P_k(v) + \sum_{j \geq 1} B_{kj} \dot{\beta}_j(\tau), \quad (0.9)$$

where the drift  $P_k$  and the dispersion  $B_{kj}$  are written explicitly in terms of the r.h.s. of eq. (0.4). It turns out that the Hamiltonian term  $-i\gamma_I f_q(|u|^2)u$  contributes to  $P(v)$  a term which disappears in the averaged  $I$ -equations. We remove it from  $P(v)$  and denote the rest  $\tilde{P}(v)$ . For any vector  $\theta = (\theta_1, \theta_2, \dots) \in \mathbb{T}^\infty$  denote by  $\Phi_\theta$  the linear transformation of the space of complex vectors  $v$  which multiplies each component  $v_j$  by  $e^{i\theta_j}$ . Following [Kuk10] we average the vector field  $\tilde{P}$  by actions of the transformations  $\Phi_\theta$  and get the *effective drift*  $R(v) = \int_{\mathbb{T}^\infty} \Phi_{-\theta} \tilde{P}(\Phi_\theta v) d\theta$ . In Section 3.1 we show that

$$R_k(v) = -\lambda_k v_k + R_k^0(v), \quad (0.10)$$

where  $R^0(v)$  is a smooth locally Lipschitz nonlinearity.

Since the noise in (0.9) is additive (i.e., the matrix  $B$  is  $v$ -independent), then construction of the effective dispersion, given in [Kuk10] for non-additive noise, simplifies significantly and defines the effective noise for eq. (0.9) whose  $k$ -th

component equals  $(\sum_l b_l^2 \Psi_{kl}^2)^{1/2} d\beta_k(\tau)$ . Accordingly the effective equations for (0.4) become

$$\dot{v}_k = R_k(v) d\tau + \left( \sum_l b_l^2 \Psi_{kl}^2 \right)^{1/2} d\beta_k(\tau), \quad k \geq 1. \quad (0.11)$$

By construction this system is invariant under rotations: if  $v(\tau)$  is its weak solution, then  $\Phi_\theta v(\tau)$  also is a weak solution. Due to (0.10) this is the heat equation  $\dot{u} = -Au$  for a complex function  $u(\tau, x)$ , perturbed by a non-local smooth non-linearity and a non-degenerate smooth noise, written in terms of the complex Fourier coefficients  $v_j$ . It turns out to be a monotone equation, so its solution is unique (see Section 3.2).

In particular, if in (0.4)  $p = 1$ , then the system of effective equations takes the form

$$\dot{v}_k = -v_k((\lambda_k - M_k) + \gamma_R \sum_l |v_l|^2 L_{kl}) d\tau + \left( \sum_l b_l^2 \Psi_{kl}^2 \right)^{1/2} d\beta_k(\tau), \quad k \geq 1, \quad (0.12)$$

where  $M_k = \int V(x) \varphi^2(x) dx$  and  $L_{kl} = (2 - \delta_{kl}) \int \varphi_k^2(x) \varphi_l^2(x) dx$ . See Example 3.1 (the calculations, made there for  $d = 1$ , remain the same for  $d \geq 2$ ).

It follows directly from the construction of effective equations that actions  $\{I(v_k(\tau)) = \frac{1}{2}|v_k(\tau)|^2, k \geq 1\}$  of any solution  $v(\tau)$  of (0.11) is a solution of the system of averaged  $I$ -equations. On the contrary, every solution  $I^0(\tau)$  of the averaged  $I$ -equations, obtained as a limit (0.8), can be lifted to a weak solution of (0.11). Using the uniqueness we get

**Theorem 0.1.** *Let  $I^\nu(\tau) = I(u^\nu(\tau))$ , where  $u^\nu(\tau)$ ,  $0 \leq \tau \leq T$ , is a solution of (0.4), (0.5). Then  $\lim_{\nu \rightarrow 0} \mathcal{D}(I^\nu(\cdot)) = \mathcal{D}(I^0(\cdot))$ , where  $I^0(\tau)$ ,  $0 \leq \tau \leq T$ , is a weak solution of the averaged  $I$ -equations. Moreover, there exists a unique solution  $v(\tau)$  of (0.11) such that  $v(0) = v_0 = \Psi(u_0)$  and  $\mathcal{D}(I(v(\cdot))) = \mathcal{D}(I^0(\cdot))$ , where  $I(v(\tau))_j = \frac{1}{2}|v_j(\tau)|^2$ .*

The solutions  $I^0(\tau)$  and  $v(\tau)$  satisfy some apriori estimates, see Theorem 3.5. Concerning distribution of the angles  $\varphi(u^\nu(\tau))$  and their joint distribution with the actions see Section 2.4.

Now let  $\mu^\nu$  be the unique stationary measure for eq. (0.4) and  $u'^\nu$  be a corresponding stationary solution,  $\mathcal{D}(u'^\nu(\tau)) \equiv \mu^\nu$ . As above, along sequences  $\nu_j \rightarrow 0$  the actions  $I'^{\nu_j}(\tau) = I(u'^{\nu_j}(\tau))$  converge in distribution to stationary solutions  $I'(\tau)$  of the averaged  $I$ -equations. These solutions can be lifted to stationary

weak solutions  $v'(\tau)$  of effective equations (0.11). Since that system is monotone, then its stationary measure  $m$  is unique. So the limit above holds as  $\nu \rightarrow 0$ . As the effective system is rotation invariant, then in the  $(I, \varphi)$ -variables its unique stationary measure has the form  $dm = m_I(dI) \times d\varphi$ . It turns out that the measure  $\lim_{\nu \rightarrow 0} \mu^\nu$  also has the rotation-invariant form and we arrive at the following result (see Theorem 4.3, 4.4 for a precise statement):

**Theorem 0.2.** *When  $\nu \rightarrow 0$  we have the convergences  $\mathcal{D}(I(u^\nu(\cdot))) \rightharpoonup \mathcal{D}I(v'(\cdot))$  and  $\Psi \circ \mu^\nu \rightharpoonup m$ , where  $dm = m_I(dI) \times d\varphi$ .*

Accordingly every solution  $u^\nu(\tau)$  of (0.2) obeys the following double limit

$$\lim_{\nu \rightarrow 0} \lim_{t \rightarrow \infty} \mathcal{D}(u^\nu(t)) = \Psi^{-1} \circ m. \quad (0.13)$$

By Theorems 0.1 and 0.2, the actions  $I(u^\nu(\tau))$  of a solution  $u^\nu$  of (0.4), (0.5) converge in distribution to those of a solution  $v(\tau)$  of the effective system (0.11) with  $v(0) = \Psi(u_0)$ , both for  $0 \leq \tau \leq T$  and when  $\tau \rightarrow \infty$ . We conjecture that this convergence hold for each  $\tau \geq 0$ , uniformly in  $\tau$  (the space of measures is equipped with the Wasserstein distance).

In Example 4.6 we discuss Theorem 0.2 for equations with  $p = 1$ , when the effective equations become (0.12). In particular, we show that Theorem 0.2 implies that in equations (0.2) with small  $\nu$  there is no direct or inverse cascade of energy.

In Example 4.5 we discuss Theorem 0.2 for the case  $\gamma_R = 0$  (when the non-linear part of the perturbation is Hamiltonian) and its relation to the theory of weak turbulence.

We note that the effective equations (0.11) depend on the potential  $V(x)$  in a regular way and are well defined without assuming that  $V(x)$  is nonresonant (cf. equations (0.12)). In particular, if  $V^M(x) \rightarrow 1$  as  $M \rightarrow \infty$ , where each  $V^M(x) \geq 1$  is a non-resonant potential, then in (0.13)  $m^M \rightharpoonup m(1)$ , where  $m(1)$  is a unique stationary measure for eq. (0.12) with  $V(x) \equiv 1$ . In this equation  $\Psi_{kl} = \delta_{k,l}$ ,  $M_k \equiv 1$  and the constants  $L_{kl}$  can be written down explicitly.

In Section 5 we show that Theorems 0.1, 0.2 remain true for 1d equations with non-viscous damping (when  $\Delta u$  in the l.h.s. of (0.2) is removed, but  $\gamma_R > 0$ ).

**Inviscid Limit.** A stationary measure  $\mu^\nu$  for eq. (0.4) also is stationary for the fast-time equation (0.2). Let  $U^\nu(t)$  be a corresponding stationary solution,  $\mathcal{D}U^\nu(t) \equiv \mu^\nu$ . It is not hard to see that the system of solutions  $U^\nu(t)$  is tight on

any finite time-interval  $[0, \tilde{T}]$ . Let  $\{U^{\nu_j}, \nu_j \rightarrow 0\}$ , be a converging subsequence, i.e.

$$\mathcal{D}(U^{\nu_j}) \rightharpoonup Q^*, \quad \mu^{\nu_j} \rightharpoonup \mu^*.$$

Then  $\mu^*$  is an invariant measure for the linear equation (0.1) and  $Q^* = \mathcal{D}(U^*(\cdot))$ , where  $U^*(t), 0 \leq t \leq \tilde{T}$ , is a stationary process such that  $\mathcal{D}(U^*(t)) \equiv \mu^*$  and every trajectory of  $U^*$  is a solution of (0.1). The limit  $\mathcal{D}(U^{\nu_j}) \rightharpoonup \mathcal{D}(U^*)$  is the *inviscid limit for eq. (0.2)*. Eq. (0.1) has plenty of invariant measures: if we write it in the action-angle variables (0.6), then every measure of the form  $m(dI) \times d\varphi$  is invariant (see [KS04] for the more complicated inviscid limit for nonlinear Schrödinger equation). Theorem 0.2 explains which one is chosen by eq. (0.2) for the limit  $\lim_{\nu \rightarrow 0} \mu^\nu$ .

The inviscid limit for the damped/driven KdV equation, studied in [KP08, Kuk10] is similar: the limit of the stationary measures for the perturbed equations is a stationary measure of the corresponding effective equations. Due to a complicated structure of the nonlinear Fourier transform which integrates KdV, uniqueness of their invariant measure is not proved yet. So the final results concerning the damped/driven KdV are less complete than those for the weakly perturbed CGL equation in Theorem 0.2.

Finally consider the damped/driven 2d Navier-Stokes equations with a small viscosity  $\nu$  and a random force, similar to the forces above and proportional to  $\sqrt{\nu}$ :

$$v'_t - \nu \Delta v + (v \cdot \nabla)v + \nabla p = \sqrt{\nu} \eta(t, x); \quad \operatorname{div} v = 0, \quad v \in \mathbb{R}^2, \quad x \in \mathbb{T}^2 \quad (0.14)$$

It is known that (0.14) has a unique stationary measure  $\mu^\nu$ , the family of measures  $\{\mu^\nu, 0 < \nu \leq 1\}$  is tight, and every limiting measure  $\lim_{\nu_j \rightarrow 0} \mu^{\nu_j}$  is a non-trivial invariant measure for the 2d Euler equation  $(0.14)_{\nu=0}$ , see Section 5.2 of [KS10]. However it is non-clear if the limiting measure is unique and how to single it out among all invariant measures of the Euler equation. The research [KP08, Kuk10] was motivated by the belief that the damped/driven KdV is a model for (0.14). Unfortunately, we still do not know up to what extend the description of the inviscid limit for the damped/driven KdV and for weakly nonlinear CGL in terms of the effective equations is relevant for the inviscid limit of the 2d hydrodynamics.

*Agreements.* Analyticity of maps  $B_1 \rightarrow B_2$  between Banach spaces  $B_1$  and  $B_2$ , which are the real parts of complex spaces  $B_1^c$  and  $B_2^c$ , is understood in the sense of Fréchet. All analytic maps which we consider possess the following

additional property: for any  $R$  a map analytically extends to a complex  $(\delta_R > 0)$ -neighbourhood of the ball  $\{|u|_{B_1} < R\}$  in  $B_1^c$ .

*Notations.*  $\chi_A$  stands for the indicator function of a set  $A$  (equal 1 in  $A$  and equal 0 outside  $A$ ). By  $\varkappa(t)$  we denote various functions of  $t$  such that  $\varkappa(t) \rightarrow 0$  when  $t \rightarrow \infty$ , and by  $\varkappa_\infty(t)$  denote functions  $\varkappa(t)$  such that  $\varkappa(t) = o(t^{-N})$  for each  $N$ . We write  $\varkappa(t) = \varkappa(t; R)$  to indicate that  $\varkappa(t)$  depends on a parameter  $R$ .

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## 1 Preliminaries

### 1.1 Apriori estimates.

We consider the 1d CGL equation on a segment  $[0, \pi]$  with a conservative linear part of order one and a small nonlinearity. The equation is supplemented with Dirichlet boundary conditions which we interpret as odd  $2\pi$ -periodic boundary conditions. Introducing the slow time  $\tau = \nu t$  (cf. Introduction) we write the equation as follows:

$$\begin{aligned} \dot{u} + i\nu^{-1}(-u_{xx} + V(x)u) &= \varkappa u_{xx} - \gamma_R |u|^{2p} u - i\gamma_I |u|^{2q} u \\ &+ \frac{d}{d\tau} \sum_{j=1}^{\infty} b_j \beta_j(\tau) e_j(x), \quad u(x) \equiv u(x + 2\pi) \equiv -u(-x). \end{aligned} \quad (1.1)$$

Here  $\dot{u} = \frac{d}{d\tau} u$ ,  $p, q \in \mathbb{Z}_+ := \mathbb{N} \cup \{0\}$  (only for simplicity, see next section),  $\varkappa > 0$ , constants  $\gamma_R$  and  $\gamma_I$  satisfy (0.3) and  $\mathbb{R} \ni V(x) \geq 0$  is a sufficiently smooth even  $2\pi$ -periodic function,  $\{e_j, j \geq 1\}$  is the sine-basis,

$$e_j(x) = \frac{1}{\sqrt{\pi}} \sin jx,$$

and  $\beta_j, j \geq 1$ , are standard independent complex Wiener processes. That is,  $\beta_j(\tau) = \beta_j(\tau) + i\beta_{-j}(\tau)$ , where  $\beta_{\pm j}(\tau)$  are standard independent real Wiener processes. Finally, the real numbers  $b_j$  all are non-zero and decay when  $j$  grows in such a way that  $B_1 < \infty$ , where

$$B_r := 2 \sum_{j=1}^{\infty} j^{2r} b_j^2 \leq \infty \quad \text{for } r \geq 0.$$



By  $\mathcal{H}^r$ ,  $r \in \mathbb{R}$  we denote the Sobolev space of order  $r$  of complex odd periodic functions and provide it with the homogeneous norm  $\|\cdot\|_r$ ,

$$\|u\|_r^2 = \sum_{l=1}^{\infty} |u_l|^2 l^{2r}, \quad \|\cdot\|_0 = \|\cdot\|$$

(if  $r \in \mathbb{N}$ , then  $\|u\|_r = \left| \frac{\partial^r u}{\partial x^r} \right|_{L_2}$ ).

Let  $u(t, x)$  be a solution of (1.1) such that  $u(0, x) = u_0$ . Applying Ito's formula to  $\frac{1}{2}\|u\|^2$  we get that

$$d\left(\frac{1}{2}\|u\|^2\right) = (-\gamma_r |u|_{2p+2}^{2p+2} - \varkappa \|u\|_1^2 + \frac{1}{2}B_0)d\tau + dM(\tau), \quad (1.2)$$

where  $M(\tau)$  is the martingale  $\int_0^\tau \sum b_j u_j \cdot d\beta_j(\tau)$ . Here  $|u|_r$  stands for the  $L_r$ -norm,  $1 \leq r \leq \infty$ , and for complex numbers  $z_1, z_2$  we denote by  $z_1 \cdot z_2$  their real scalar product,

$$z_1 \cdot z_2 = \operatorname{Re} z_1 \overline{z_2}.$$

So  $(u_j + iu_{-j}) \cdot (d\beta_j + id\beta_{-j}) = u_j d\beta_j + u_{-j} d\beta_{-j}$ . From (1.2) we get in the usual way (e.g., see Section 2.2.3 in [KS10]) that

$$\mathbf{E} e^{\rho \varkappa \|u(\tau)\|^2} \leq C(\varkappa, B_0, \|u_0\|) \quad \forall \tau \geq 0 \quad (1.3)$$

for a suitable  $\rho \varkappa > 0$ , uniformly in  $\nu > 0$ .

Denoting

$$\mathcal{E}(\tau) = \frac{1}{2}\|u(\tau)\|^2 + \gamma_r \int_0^\tau |u|_{2p+p}^{2p+p} ds + \frac{\varkappa}{2} \int_0^\tau \|u\|_1^2 ds$$

and noting that the characteristic of the martingale  $M$  is  $\langle M \rangle(\tau) = \sum b_j^2 |u_j|^2 \leq b_M^2 \|u\|^2$ , where  $b_M = \max |b_j|$ , we get from (1.2) that

$$\begin{aligned} \mathcal{E}(\tau) &\leq \frac{1}{2}\|u_0\|^2 + \frac{1}{2}B_0\tau + M(\tau) - \frac{\varkappa}{2} \int_0^\tau \|u\|^2 ds \\ &\leq \frac{1}{2}\|u_0\|^2 + \frac{1}{2}B_0\tau + \varkappa^{-1}b_M^2 \left[ (\varkappa b_M^{-2} M(\tau)) - \frac{1}{2} \langle \varkappa b_M^{-2} M \rangle(\tau) \right]. \end{aligned}$$

Applying in a standard way the exponential supermartingale estimate to the term in the square bracket in the r.h.s. (e.g., see [KS10], Section 2.2.3), we get that

$$\mathbf{P}\left\{\sup_{\tau \geq 0} (\mathcal{E}(\tau) - \frac{1}{2}B_0\tau) \geq \frac{1}{2}\|u_0\|^2 + \rho\right\} \leq e^{-2\rho \varkappa b_M^{-2}}, \quad (1.4)$$

for any  $\rho > 0$ .

Now let us re-write eq. (1.1) as follows:

$$\dot{u} + i\nu^{-1}(-u_{xx} + V(x)u + \nu\gamma_I|u|^{2q}u) = \varkappa u_{xx} - \gamma_R|u|^{2p}u + \frac{d}{d\tau} \sum b_j \beta_j(\tau) e_j. \quad (1.5)$$

The l.h.s. is a Hamiltonian system with the hamiltonian  $-\nu^{-1}H(u)$ ,

$$H(u) = \frac{1}{2}\langle Au, u \rangle + \gamma_I \frac{\nu}{2q+2} \int |u|^{2q+2} dx, \quad A = -\frac{\partial^2}{\partial x^2} + V(x).$$

For any  $j \in \mathbb{N}$  we denote

$$\|u\|_r'^2 = \langle A^r u, u \rangle.$$

Then  $dH(u)(v) = \langle Au, v \rangle + \gamma_I \nu \langle |u|^{2q} u, v \rangle$  and

$$\frac{1}{2} \cdot 2 \sum_{j=1}^{\infty} b_j^2 d^2 H(u)(e_j, e_j) = \frac{1}{2} B'_1 + \gamma_I \nu X(\tau),$$

where

$$B'_r = 2 \sum b_j^2 \|e_j\|_r'^2 = 2 \sum b_j^2 \lambda_j^r \quad \forall r,$$

and

$$\begin{aligned} X(\tau) &= 2p \operatorname{Re} \int \left( |u|^{2q-2} u^2 \sum_j b_j^2 e_j(x)^2 \right) dx + \int |u|^{2q} \sum_j b_j^2 e_j(x)^2 dx \\ &\leq C B_0 |u(\tau)|_{2q}^{2q}. \end{aligned}$$

Therefore applying Ito's formula we get that

$$\begin{aligned} dH(u(\tau)) &= \left( (-\gamma_R \langle Au, |u|^{2p} u \rangle + \varkappa \langle Au, u_{xx} \rangle - \gamma_I \nu \gamma_R \int |u|^{2p+2q+2} dx \right. \\ &\quad \left. + \varkappa \gamma_I \nu \langle |u|^{2q} u, u_{xx} \rangle + B'_1 + \gamma_I \nu X(\tau) \right) d\tau + dM(\tau), \end{aligned} \quad (1.6)$$

where  $dM(\tau) = \sum b_j \langle Au + \gamma_I \nu |u|^{2q} u, e_j \rangle \cdot d\beta_j(\tau)$ .

Denoting  $U_q(x) = \frac{1}{q+1} u^{q+1}$  and  $U_p(x) = \frac{1}{p+1} u^{p+1}$ , we have

$$\langle |u|^{2q} u, u_{xx} \rangle \leq - \int |u_x|^2 |u|^{2q} dx = - \left\| \frac{\partial}{\partial x} U_q \right\|^2,$$

and a similar relation holds for  $q$  replaced by  $p$ . Accordingly,

$$\begin{aligned} dH(u(\tau)) \leq & -\frac{1}{2} \left( \varkappa \|u\|_2^2 + \gamma_R \left\| \frac{\partial}{\partial x} U_p \right\|^2 + \varkappa \gamma_I \nu \left\| \frac{\partial}{\partial x} U_q \right\|^2 \right. \\ & \left. + \nu \gamma_I \gamma_R \int |u|^{2p+2q+2} dx - C_\varkappa \|u\|^2 - 2B'_1 \right) d\tau + dM(\tau), \end{aligned} \quad (1.7)$$

where  $C_\varkappa$  may be chosen independent from  $\varkappa$  if  $\gamma_R > 0$ . Considering relations on  $H(u)^m$ ,  $m \geq 1$ , which follow from (1.7) and (1.6), using (1.4) and arguing by induction we get that

$$\mathbf{E} \left( \sup_{0 \leq t \leq T} H(u(t))^m + \frac{\varkappa}{2} \int_0^T H^{m-1} \|u\|_2^2 ds \right) \leq H(u_0)^m + C_m(\varkappa, T, B_1)(1 + \|u_0\|^{c_m}), \quad (1.8)$$

$$\mathbf{E} H(u(t))^m \leq C_m(\varkappa, B_1)(1 + H(u_0)^m + \|u_0\|^{c_m}) \quad \forall t > 0. \quad (1.9)$$

Estimates (1.8) in a traditional way (cf. [Hai02, KS04, Oda06, Shi06]) imply that eq. (1.1) is *regular in space*  $\mathcal{H}^1$  in the sense that for any  $u_0 \in \mathcal{H}^1$  it has a unique strong solution, satisfying (1.4), (1.8)

## 1.2 Stationary measures.

The a-priori estimates on solutions of (1.1) and the Bogolyubov-Krylov argument (e.g., see in [KS10]) imply that eq. (1.1) has a stationary measure  $\mu^\nu$ , supported by space  $\mathcal{H}^2$ . Now assume that

$$b_j \neq 0 \quad \forall j. \quad (1.10)$$

Then the approaches, developed in the last decade to study the 2d stochastic Navier-Stokes equations, apply to (1.1) and allow to prove that under certain restrictions on the equation the stationary measure  $\mu^\nu$  is unique. In particular this is true if  $\gamma_I = 0$  (the easiest case), or if  $p \geq q$  and  $\gamma_R \neq 0$  (see [Oda06]), or if  $\gamma_R = 0$  and  $p = 1$  (see [Shi06]). In this case any solution  $u(t)$  of (1.1) with  $u(0) = u_0 \in \mathcal{H}^1$  satisfies

$$\mathcal{D}u(t) \rightharpoonup \mu^\nu \quad \text{as } t \rightarrow \infty. \quad (1.11)$$

This convergence and (1.3), (1.9) imply that

$$\int e^{\rho \varkappa \|u\|^2} \mu^\nu(du) \leq C(\varkappa, B), \quad (1.12)$$

$$\int \|u\|_1^{2m} \mu^\nu(du) \leq C_m(\varkappa, B_1) \quad \forall m. \quad (1.13)$$

### 1.3 Multidimensional case.

In this section we briefly discuss a multidimensional analogy of eq. (1.1):

$$\begin{aligned} \dot{u} + i\nu^{-1}Au &= \Delta u - \gamma_R f_p(|u|^2)u - i\gamma_I f_q(|u|^2)u \\ &+ \frac{d}{d\tau} \sum_{j=1}^{\infty} b_j \beta_j(\tau) e_j(x), \quad u = u(\tau, x), \quad x \in \mathbb{T}^d. \end{aligned} \quad (1.14)$$

Here  $Au = -\Delta u + V(x)u$ ,  $V \in C^N(\mathbb{T}^d, \mathbb{R})$  and  $V(x) \geq 1$ . The numbers  $\gamma_I, \gamma_R$  satisfy (0.3). Functions  $f_p \geq 0$  and  $f_q \geq 0$  are real-valued smooth and

$$f_p(t) = t^p \quad \text{for } t \geq 1, \quad f_q(t) = t^q \quad \text{for } t \geq 1,$$

where  $p, q \geq 0$ . If  $\gamma_R = 0$ , then the term  $\Delta u$  in the r.h.s. should be modified to  $\Delta - u$ . By  $\{e_k, k \geq 1\}$ , we denote the usual trigonometric basis of the space  $L_2(\mathbb{T}^d)$  (formed by all functions  $\pi^{-d/2} f_{s_1}(x_1) \dots f_{s_d}(x_d)$ , where each  $f_s(x)$  is  $\sin sx$  or  $\cos sx$ ), parameterised by natural numbers. These are eigen-functions of the Laplacian,  $-\Delta e_r = \lambda_r e_r$ . We assume that

$$B'_{N_1} = 2 \sum_k \lambda_k^{N_1} b_k^2 < \infty, \quad (1.15)$$

where  $N_1 = N_1(d)$  is sufficiently large. In this section we denote by  $(\mathcal{H}^r, \|\cdot\|_r)$  the Sobolev space  $\mathcal{H}^r = H^r(\mathbb{T}^d, \mathbb{C})$ , regarded as a real Hilbert space, and  $\langle \cdot, \cdot \rangle$  stands for the real  $L_2$ -scalar product.

Noting that  $(f_p(|u|^2)u - |u|^{2p}u)$  and  $(f_q(|u|^2)u - |u|^{2q}u)$  are bounded Lipschitz functions with compact support we immediately see that the a-priori estimates from Section 1.1 remain true for solutions of (1.14). Accordingly, for any  $u_0 \in \mathcal{H}^1 \cap L_{2q+2}$  eq. (1.1) has a solution  $u(t, x)$  such that  $u(0, x) = u_0$ , satisfying (1.3), (1.8), (1.9).

Now assume that

$$p, q < \infty \quad \text{if } d = 1, 2, \quad p, q < \frac{2}{d-2} \quad \text{if } d \geq 3. \quad (1.16)$$

Applying Ito's formula to the processes  $\langle A^m u(\tau), u(\tau) \rangle^n$ ,  $m, n \geq 1$ , using (1.3), (1.8), (1.9) and arguing by induction (first in  $n$  and next in  $m$ ) we get that

$$\begin{aligned} \mathbf{E} \left( \sup_{0 \leq \tau \leq T} \|u(\tau)\|_{2m}^{2n} + \int_0^T \|u(s)\|_{2m+1}^2 \|u(s)\|_{2m}^{2n-2} ds \right) \\ \leq \|u_0\|_{2m}^{2n} + C(m, n, T) (1 + \|u_0\|^{c_{m,n}}), \end{aligned} \quad (1.17)$$

$$\mathbf{E} \|u(\tau)\|_{2m}^{'2n} \leq C(m, n) \quad \forall \tau \geq 0, \quad (1.18)$$

for each  $m$  and  $n$ , where  $C(m, n, T)$  and  $C(m, n)$  also depends on  $|V|_{C^N}$  and  $B_{N_1}$  (see (1.15)), and  $N = N(m)$ ,  $N_1 = N_1(m)$ .

Relations (1.17) with  $m = m_0 \geq 1$  in the usual way (cf. [Hai02, KS04, Oda06, Shi06]) imply that eq. (1.14) is *regular in the space*  $\mathcal{H}^{m_0} \cap L_{2q+2}$  in the sense that for any  $u_0 \in \mathcal{H}^{m_0} \cap L_{2q+2}$  it has a unique strong solution  $u(t, x)$ , equal  $u_0$  at  $t = 0$ , and satisfying estimates (1.3), (1.17) with  $m = m_0$  for any  $n$ . By the Bogolyubov-Krylov argument this equation has a stationary measure  $\mu^\nu$ , supported by the space  $\mathcal{H}^{m_0} \cap L_{2q+2}$ , and a corresponding stationary solution  $u^\nu(\tau)$ ,  $\mathcal{D}u^\nu(\tau) \equiv \mu^\nu$ , also satisfies (1.3) and (1.18) with  $m = m_0$ .

If (1.10) holds and (1.16) is replaced by a stronger assumption, then a stationary measure is unique. If  $\gamma_I = 0$ , the uniqueness readily follows, for example, from the abstract theorem in [KS10]. In [Shi06] this assertion is proved if

$$\gamma_R = 0 \text{ and } q \leq 1 \text{ if } d = 1, \quad q < 1 \text{ if } d = 2, \quad q \leq 2/d \text{ if } d = 3. \quad (1.19)$$

In [Oda06] it is established if

$$p = q, \gamma_R, \gamma_I > 0 \text{ if } d = 1, 2, \quad \text{and } p = q < \frac{2}{d-2}, \gamma_R, \gamma_I > 0 \text{ if } d \geq 3; \quad (1.20)$$

the argument of this work also applies if  $p > q$ .

Note that when  $\gamma_R = 0$  or when  $p < q$  (i.e., when the nonlinear damping is weaker than the conservative term), the assumptions (1.19), (1.20), needed for the uniqueness of the stationary measure, are much stronger than the assumptions (1.16), needed for the regularity. This gap does not exist (at least it shrinks a lot) if the random force in eq. (1.14) is not white in time, but is a kick-force. See in [KS00] the abstract theorem and its application to the CGL equations.

## 1.4 Spectral properties of $A_V$ : one-dimensional case.

As in Section 1.1 we denote  $A_V = A = -\partial^2/\partial x^2 + V(x)$ , where the potential  $V(x) \geq 0$  belongs to the space  $C_e^N$  of  $C^N$ -smooth even and  $2\pi$ -periodic functions,  $N \geq 1$ . Let  $\varphi_1, \varphi_2, \dots$  be the  $L_2$ -normalised complete system of eigenfunctions of  $A_V$  with the eigenvalues  $1 \leq \lambda_1 < \lambda_2 < \dots$ . Consider the linear mapping

$$\Psi : \mathcal{H} \ni u(x) \mapsto v = (v_1, v_2, \dots) \in \mathbb{C}^\infty,$$

defined by the relation  $u(x) = \sum v_k \varphi_k(x)$ . In the space of complex sequences  $v$  we introduce the norms

$$|v|_{h^m}^2 = \sum_{k \geq 1} |v_k|^2 \lambda_k^m, \quad m \in \mathbb{R},$$

and denote  $h^m = \{v \mid |v|_{h^m} < \infty\}$ . Due to the Parseval identity,  $\Psi : \mathcal{H} \rightarrow h^0$  is a unitary isomorphism. For any  $m \in \mathbb{N}$  we have  $|v|_{h^m}^2 = \langle A^m u(x), u(x) \rangle$ . So the norms  $|v|_{h^m}$  and  $\|u\|_m$  are equivalent for  $m = 0, \dots, N$ . Since  $\Psi^* = \Psi^{-1}$ , then the norms are equivalent for integer  $|m| \leq N$ . By interpolation they are equivalent for all real  $|m| \leq N$ . So

$$\text{the maps } \Psi : \mathcal{H}^m \rightarrow h^m, \quad |m| \leq N, \quad \text{are isomorphisms.} \quad (1.21)$$

Denote  $G = \Psi^{-1} : h^m \rightarrow \mathcal{H}^m$ . Then

$$\Psi \circ A \circ G = \text{diag}\{\lambda_k, k \geq 1\} =: \hat{A}.$$

Consider the operator

$$\mathcal{L} := \Psi \circ (-\Delta) \circ G = \Psi \circ (A - V) \circ G = \hat{A} - \Psi \circ V \circ G =: \hat{A} - \mathcal{L}^0. \quad (1.22)$$

By (1.21)  $\mathcal{L}^0 = \Psi \circ V \circ G$  defines bounded maps

$$\mathcal{L}^0 : h^m \rightarrow h^m \quad \forall |m| \leq N, \quad (1.23)$$

and in the space  $h^0$  it is selfadjoint.

For any finite  $M$  consider the mapping

$$\Lambda^M : C_e^N \rightarrow \mathbb{R}^M, \quad V(x) \mapsto (\lambda_1, \dots, \lambda_M).$$

Since the eigenvalues  $\lambda_j$  are different, the mapping is analytic. As the functions  $\varphi_1^2, \varphi_2^2, \dots$  are linearly independent by the classical result of G. Borg, then for any  $V \in C_e^N$  the linear mapping

$$d\Lambda^M(V) : C_e^N \rightarrow \mathbb{R}^M \quad \text{is surjective.} \quad (1.24)$$

In the space  $C_e^N$  consider a Gaussian measure  $\mu_K$  with a non-degenerate correlation operator  $K$  (so for the quadratic function  $f(V) = \langle V, \xi \rangle_{L_2} \langle V, \eta \rangle_{L_2}$  we have  $\int f(V) \mu_K(dV) = \langle K\xi, \eta \rangle$ ). Relation (1.24) easily implies

**Lemma 1.1.** *For any  $M \geq 1$  the measure  $\Lambda^M \circ \mu_K$  is absolutely continuous with respect to the Lebesgue measure on  $\mathbb{R}^M$ .*

We will call a vector  $\Lambda \in \mathbb{R}^\infty$  *nonresonant* if for any non-zero integer vector  $s$  of finite length we have

$$\Lambda \cdot s \neq 0. \quad (1.25)$$

A potential  $V(x)$  is called nonresonant if its spectrum  $\Lambda(V) = (\lambda_1, \lambda_2, \dots)$  is nonresonant. The nonresonant potentials are defined in  $C_e^N$  by a countable family of open dense relations (1.25). So

$$\begin{aligned} &\text{the nonresonant potentials form a subset of } C_e^N \\ &\text{of the second Baire category.} \end{aligned} \quad (1.26)$$

Applying Lemma 1.1 we also get

$$\text{the nonresonant potentials form a subset of } C_e^N \text{ of full } \mu_K \text{ measure,} \quad (1.27)$$

for any Gaussian measure  $\mu_K$  as above.

The non-resonant vectors  $\Lambda$  are important because of the following version of the Kronecker-Weyl theorem:

**Lemma 1.2.** *Let  $f \in C^{n+1}(\mathbb{T}^n)$  for some  $n \in \mathbb{N}$ . Then for any nonresonant vector  $\Lambda$  we have*

$$\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T f(q_0 + t\Lambda^n) dt = (2\pi)^{-n} \int f dx, \quad \Lambda^n = (\Lambda_1, \dots, \Lambda_n),$$

*uniformly in  $q_0 \in \mathbb{T}^n$ . The rate of convergence depends on  $n$ ,  $\Lambda$  and  $|f|_{C^{n+1}}$ .*

*Proof.* Let us write  $f(q)$  as the Fourier series  $f(q) = \sum f_s e^{is \cdot q}$ . Then for each non-zero  $s$  we have  $|f_s| \leq C_{n+1} |f|_{C^{n+1}} |s|^{-n-1}$ . So for any  $\varepsilon > 0$  we may find  $R = R_\varepsilon$  such that  $\left| \sum_{|s| > R} f_s e^{is \cdot q} \right| \leq \frac{\varepsilon}{2}$  for each  $q$ . Now it suffices to show that

$$\left| \frac{1}{T} \int_0^T f_R(q_0 + t\Lambda^n) dt - f_0 \right| \leq \frac{\varepsilon}{2} \quad \forall T \geq T_\varepsilon \quad (1.28)$$

for a suitable  $T_\varepsilon$ , where  $f_R(q) = \sum_{|s| \leq R} f_s e^{is \cdot q}$ . But

$$\left| \frac{1}{T} \int_0^T e^{is \cdot (q_0 + t\Lambda^n)} dt \right| \leq \frac{2}{T |s \cdot \Lambda^n|},$$

for each nonzero  $s$ . Therefor the l.h.s. of (1.28) is

$$\leq \frac{2}{T} \left( \inf_{|s| \leq R} |s \cdot \Lambda^n| \right)^{-1} \sum |f_s| \leq T^{-1} |f|_{C^0} C(R, \Lambda).$$

Now the assertion follows.  $\square$

## 1.5 Spectral properties of $A_V$ : multi-dimensional case.

Now let, as in Section 1.3,  $A = A_V$  be the operator  $A = -\Delta + V(x)$ ,  $x \in \mathbb{T}^d$ , where  $1 \leq V(x) \in C^N(\mathbb{T}^d)$ . Let  $\{\varphi_k(x), k \geq 1\}$  be its  $L_2$ -normalised eigenfunctions and  $\{\lambda_k, k \geq 1\}$ , be the corresponding eigenvalues,  $1 \leq \lambda_1 \leq \lambda_2 \leq \dots$ . For any  $M \geq 1$  denote by  $F_M \subset C^N(\mathbb{T}^d)$  the open domain

$$F_M = \{V \mid \lambda_1 < \lambda_2 < \dots < \lambda_M\}.$$

Its complement  $F_M^c$  is a real analytic variety in  $C^N(\mathbb{T}^d)$  of codimension  $\geq 2$ , so  $F_M$  is connected (see [KK95] and references therein). The functions  $\lambda_1, \dots, \lambda_M$  are analytic in  $F_M$ . Let us fix any non-zero vector  $s \in \mathbb{Z}^\infty$  such that  $s_l = 0$  for  $l > M$ . The set

$$Q_s = \{V \in F_M \mid \Lambda(V) \cdot s = 0\}$$

clearly is closed in  $F_M$ . Since the function  $\Lambda(V) \cdot s$  is analytic in  $F_M$ , then either  $Q_s = F_M$ , or  $Q_s$  is nowhere dense in  $F_M$ . Theorem 1 from [KK95] immediately implies that  $Q_s \neq F_M$ , so (1.26) also holds true in the case we consider now.

Let  $\mu_K$  be a Gaussian measure with a non-degenerate correlation operator, supported by the space  $C^N(\mathbb{T}^d)$ . As  $\Lambda(V) \cdot s$  is a non-trivial analytic function on  $F_M$  and  $F_M^c$  is an analytic variety of positive codimension, then  $\mu_K(Q_s) = 0$  (e.g., see Theorem 1.6 in [AKSS07]). Since this is true for any  $M$  and any  $s$  as above, then the assertion (1.27) also is true.

## 2 Averaging theorem.

The approach and the results of this section apply both to equations (1.1) and (1.14). We present it for eq. (1.1) and at Subsection 2.5 discuss small changes, needed to treat (1.14). Everywhere below  $T$  is an arbitrary fixed positive number.



## 2.1 Preliminaries.

In eq. (1.1) with  $u \in \mathcal{H}^1$  we pass to the  $v$ -variables,  $v = \Psi(u) \in h^1$ :

$$\dot{v}_k + i\nu^{-1}\lambda_k v_k = P_k(v) d\tau + \sum_{j \geq 1} B_{kj} d\beta_j(\tau), \quad k \geq 1. \quad (2.1)$$

Here  $B_{kj} = \Psi_{kj} b_j$  (a matrix with real entries, operating on complex vectors), and

$$P_k = P_k^1 + P_k^2 + P_k^3, \quad (2.2)$$

where  $P^1$ ,  $P^2$  and  $P^3$  are, correspondingly, the linear, dissipative and Hamiltonian parts of the perturbation:

$$P^1(v) = \varkappa \Psi \circ \frac{\partial^2}{\partial x^2} u, \quad P^2(v) = -\gamma_R \Psi(|u|^{2p} u), \quad P^3(v) = -i\gamma_I \Psi(|u|^{2q} u),$$

where  $u = G(v)$ . We will refer to equations (2.1) as to the  $v$ -equations.

For  $k \geq 1$  let us denote  $I_k = I(v_k) = \frac{1}{2}|v_k|^2$  and  $\varphi_k = \varphi(v_k) = \text{Arg } v_k \in S^1$ , where  $\varphi(0) = 0 \in S^1$ . Consider the mappings

$$\Pi_I : h^r \ni v \mapsto I = (I_1, I_2, \dots) \in h_{I+}^r, \quad \Pi_\varphi : h^r \ni v \mapsto \varphi = (\varphi_1, \varphi_2, \dots) \in \mathbb{T}^\infty.$$

Here  $h_{I+}^r$  is the positive octant in the space

$$h_I^r = \{I \mid |I|_{h_I^r} = 2 \sum_j j^{2r} |I_j| < \infty\}.$$

We will write

$$\Pi_I(\Psi(u)) = I(u), \quad \Pi_\varphi(\Psi(u)) = \varphi(u), \quad (\Pi_I \times \Pi_\varphi)(\Psi(u)) = (I \times \varphi)(u).$$

The mapping  $I : \mathcal{H}^r \rightarrow h_I^r$  is 2-homogeneous continuous, while the mappings  $\varphi : \mathcal{H}^r \rightarrow \mathbb{T}^\infty$  and  $(I \times \varphi) : \mathcal{H}^r \rightarrow h_I^r \times \mathbb{T}^\infty$  are Borel-measurable and discontinuous (the torus  $\mathbb{T}^\infty$  is given the Tikhonov topology and a corresponding distance).

Now let us pass in eq. (2.1) from the complex variables  $v_k$  to the real variables  $I_k \geq 0$ ,  $\varphi_k \in S^1$ :

$$dI_k(\tau) = (v_k \cdot P_k)(v) d\tau + Y_k^2 d\tau + \sum_l \Psi_{kl} b_l (v_k \cdot d\beta_l), \quad Y_k = \sqrt{\sum_l b_l^2 \Psi_{kl}^2}, \quad (2.3)$$

and

$$\begin{aligned}
d\varphi_k(\tau) &= \left( \nu^{-1}\lambda_k + |v_k|^{-2}(iv_k) \cdot P_k - |v_k|^{-2} \sum_l b_l(\Psi_{kl} \cdot v_k)(\Psi_{kl} \cdot iv_k) \right) d\tau \\
&\quad + \sum_l |v_k|^{-2} b_l \Psi_{kl}(iv_k \cdot d\beta_l) \\
&=: (\nu^{-1}\lambda_k + G_k(v)) d\tau + \sum_l g_{kl}(v) \left( \frac{iv_k}{|v_k|} \cdot d\beta_l(\tau) \right).
\end{aligned} \tag{2.4}$$

Due to (1.22), (1.23)

$$P(v) = \varkappa \hat{A}v + P^0(v), \quad P^0 : h^r \rightarrow h^r \quad \forall \frac{1}{2} < r \leq N,$$

where the map  $P^0$  is real analytic. The mapping  $P^0(v)$  and its differential  $dP^0(v)$  both have a polynomial growth in  $|v|_{h^r}$ . Therefore

$$|P(v) - P(v^m)|_{r-2-1/3} \leq m^{-1/3} Q(|v|_{h^r}),$$

where  $Q$  is a polynomial. Here for any  $v = (v_1, v_2, \dots) \in h^1$  we denote  $v^m = (v_1, \dots, v_m) \in \mathbb{C}^m$  and identify it with the vector  $(v_1, \dots, v_m, 0, \dots) \in h^1$ .

The functions  $G_k$  and  $g_{kl}$  are singular as  $v_k = 0$  and satisfy the following estimates:

$$|G_k(v) \chi_{\{|v_k| > \delta\}}| \leq \delta^{-1} Q_k(|v|_r), \tag{2.5}$$

$$|g_{kj}(v) \chi_{\{|v_k| > \delta\}}| \leq \delta^{-1} j^{-N} Q_{kN}(|v|_r), \tag{2.6}$$

where  $Q_k$  and  $Q_{kN}$  are polynomials.

For any vector  $\theta = (\theta_1, \theta_2, \dots) \in \mathbb{T}^\infty$  we denote by  $\Phi_\theta$  the unitary rotation

$$\Phi_\theta : h^r \rightarrow h^r, \quad v \mapsto v_\theta, \quad \text{where} \quad v_{\theta j} = e^{i\theta_j} v_j \quad \forall j.$$

By  $\langle F \rangle$  etc we denote the averaged functions,  $\langle F \rangle(v) = \int_{\mathbb{T}^\infty} F(\Phi_\theta v) d\theta$ . They are  $\varphi$ -independent, so  $\langle F \rangle = \langle F \rangle(\Pi_I(v))$ . The functions  $\langle P \rangle, \langle F \rangle, \dots$  also satisfy the estimates above. So

$$|\langle (v_k \cdot P_k) \rangle(I^m) - \langle (v_k \cdot P_k) \rangle(I)| \leq m^{-1/3} C_k Q(|I|_{h_1^1}),$$

where  $Q$  is a polynomial.

Since the dispersion matrix  $\{B_{kj}\}$  is non-degenerate, then repeating for equations (2.1) and (2.3) the arguments from Section 7 in [KP08] (also see Section 6.2 in [Kuk10]), we get

**Lemma 2.1.** *Let  $v^\nu(\tau)$  be a solution of (2.1) and  $I^\nu(\tau) = I(v^\nu(\tau))$ . Then for any  $k \geq 1$  the following convergence hold uniformly in  $\nu > 0$ :*

$$\int_0^T \mathbf{P}\{I_k^\nu(\tau) \leq \delta\} d\tau \rightarrow 0 \quad \text{as } \delta \rightarrow 0. \quad (2.7)$$

(Certainly the rate of the convergence depends on  $k$ .)

## 2.2 The theorem.

Let us abbreviate

$$h^1 = h, \quad h_I^1 = h_I, \quad C([0, T], h_{I+}) = \mathcal{H}_I,$$

where  $h_{I+}$  is the positive octant  $\{I \in h_I \mid I_j \geq 0 \ \forall j\}$ . Fix any  $u_0 \in h$ . Due to the estimates (1.1) and (1.9) the set of laws  $\{\mathcal{D}(I^\nu(\cdot))\}$ ,  $0 < \nu \leq 1$ , is tight in  $\mathcal{H}_I$ . Denote by  $Q^0$  any limiting measure as  $\nu = \nu_j \rightarrow 0$ , i.e.

$$\mathcal{D}(I^{\nu_j}(\cdot)) \rightharpoonup Q^0 \quad \text{as } \nu_j \rightarrow 0.$$

Let us consider the averaged drift  $(\langle (v_k \cdot P_k) \rangle(I) + Y_k^2) d\tau$  for eq. (2.3). We have

$$\langle (v_k \cdot P_k) \rangle(v) = \int_{\mathbb{T}^\infty} (e^{i\theta_k} v_k) \cdot P_k(\Phi_\theta v) d\theta = v_k \cdot R'_k(v), \quad (2.8)$$

where  $R'_k = \int_{\mathbb{T}^\infty} (e^{-i\theta_k} P_k(\Phi_\theta v)) d\theta$  (note that  $\langle (v_k \cdot P_k) \rangle$  depends only on  $I = \Pi_I(v)$ , while  $R'_k(v)$  depends on  $v$ ). The diffusion matrix for (2.3) is  $\{A_{kr}, \ k, r \geq 1\}$ , where

$$A_{kr}(v) = \sum_l (\Psi_{kr} b_l v_k) \cdot (\Psi_{rl} b_l v_r) = \sum_l b_l^2 (v_k \cdot v_r) \Psi_{kl} \Psi_{rl}.$$

Its average is

$$\begin{aligned} \langle A_{kr} \rangle(v) &= \sum_l b_l^2 \int_{\mathbb{T}^\infty} \operatorname{Re} (e^{-i(\theta_k - \theta_r)} v_k \bar{v}_r) \Psi_{kl} \Psi_{rl} d\theta \\ &= \delta_{kr} |v_k|^2 Y_k^2, \quad Y_k = \left( \sum_l b_l^2 |\Psi_{kl}|^2 \right)^{1/2}. \end{aligned} \quad (2.9)$$

Due to (1.21),

$$\sum_k Y_k^2 k^{2m} \leq C_m B_m \quad \forall m. \quad (2.10)$$

Our first goal is to prove the following averaging theorem:

**Theorem 2.2.** *The measure  $Q^0$  is a solution of the martingale problem in the space  $h_I$  with the drift  $(\langle v_k \cdot P_k \rangle(I) + Y_k^2) d\tau$  and the diffusion matrix  $\langle A_{kr} \rangle(I)$ . That is,  $Q^0 = \mathcal{D}(I^0(\cdot))$ , where the process  $I^0(\tau)$  is a weak (in the sense of stochastic analysis) solution of the averaged equations*

$$dI_k = (\langle (v_k \cdot P_k) \rangle(I) + Y_k^2) d\tau + \sum_r (\sqrt{\langle A \rangle})_{kr}(I) d\beta_r(\tau), \quad k \geq 1; \quad (2.11)$$

$I(0) = I_0 = \Pi_I(v_0)$ . Moreover,

$$\mathbf{E} \sup_{0 \leq \tau \leq T} |I^0(\tau)|_{h_I}^n \leq C_n(\|u_0\|_1^{2n} + 1) \quad \forall n, \quad (2.12)$$

$$\mathbf{E} \int_0^T |I^0(\tau)|_{h_I^2}^2 d\tau \leq C(\|u_0\|_1^2 + 1). \quad (2.13)$$

*Proof.* The crucial step of the proof is to establish the following lemma:

**Lemma 2.3.** *Let  $\tilde{F}(v)$  be an analytic function on the space  $h = h^1$  which extends to an analytic function on  $h^{2/3}$  of a polynomial growth. Then*

$$\mathfrak{A}^\nu := \mathbf{E} \max_{0 \leq \tau \leq T} \left| \int_0^\tau (\tilde{F}(I^\nu(s), \varphi^\nu(s)) - \langle \tilde{F} \rangle(I^\nu(s))) ds \right| \rightarrow 0 \quad \text{as } \nu \rightarrow 0. \quad (2.14)$$

The lemma is proved below in Section 2.3, following the argument in [KP08]. Now we derive from it the theorem. Let us equip the space  $\mathcal{H}_I$  with the Borel sigma-algebra  $\mathcal{F}$ , the natural filtration of sigma-algebras  $\{\mathcal{F}_\tau, 0 \leq \tau \leq T\}$  and the probability  $Q^0$ . The fact that the processes  $I_k^\nu(\tau) - \int_0^\tau ((v_k^\nu \cdot P_k)(v^\nu) + Y_k^2) ds$  are martingales, the convergence  $\mathcal{D}(I^{\nu_j}(\cdot)) \rightarrow Q^0$  and Lemma 2.3 with  $\tilde{F} = F_k$  imply that the processes  $Z_k(\tau) = I_k(\tau) - \int_0^\tau (\langle (v_k \cdot P_k) \rangle(I(s) + Y_k^2) ds, k \geq 1$ , are  $Q^0$ -martingales, cf. Section 6 of [KP08].

Similar to (2.14) we find that

$$\mathbf{E} \max_{0 \leq \tau \leq T} \left| \int_0^\tau (\tilde{F}(I^\nu(s), \varphi^\nu(s)) - \langle \tilde{F} \rangle(I^\nu(s))) ds \right|^4 \rightarrow 0 \quad \text{as } \nu \rightarrow 0.$$

Then using the same arguments as before, we see that the processes  $Z_k(\tau)Z_j(\tau) - \int_0^\tau \langle A_{kj} \rangle(I(s)) ds$  also are  $Q^0$ -martingales. That is,  $Q^0$  is a solution of the martingale problem with the drift  $\langle F_k \rangle + Y_k^2$  and the diffusion  $\langle A \rangle$ . Hence,  $Q^0$  is a law of a weak solution of eq. (2.11). See [Yor74].

Estimates (2.12), (2.13) follow from (1.8) and the basic properties of the weak convergence since  $\|u\|_m^2 \sim |v|_m^2 = \Pi_I(v)|_{h_I^m}$ .  $\square$

### 2.3 Proof of Lemma 2.3.

Fix any  $m \geq 1$  and denote by  $I^{\nu,m}, \varphi^{\nu,m}$  etc the vectors, formed by the first  $m$  components of the infinite vectors  $I^\nu, \varphi^\nu$ , etc. Below  $R$  denotes a suitable function of  $\nu$  such that  $R(\nu) \rightarrow \infty$  as  $\nu \rightarrow 0$ , but

$$R^N \nu \rightarrow 0 \quad \text{as} \quad \nu \rightarrow 0, \quad \forall N. \quad (2.15)$$

Denote by  $\Omega_R = \Omega_R^\nu$  the event

$$\Omega_R = \left\{ \sup_{0 \leq \tau \leq T} |v^\nu(\tau)|_{h_1} \geq R \right\}.$$

Then  $\mathbf{P}(\Omega_R) \leq \varkappa_\infty(R)$  uniformly in  $\nu$  (see Notations). We denote

$$\mathbf{P}_{\Omega_R}(Q) = \mathbf{P}(\Omega_R^c \cap Q), \quad \mathbf{E}_{\Omega_R}(f) = \mathbf{E}(f \chi_{\Omega_R^c}).$$

Since for  $|v|_{h_1} \leq R$  we have  $|v - v^m|_{h^{2/3}} \leq C(R)m^{-1/3}$  and since  $\tilde{F}$  is Lipschitz on  $h^{2/3}$ , then

$$\mathfrak{A}^\nu \leq \varkappa_\infty(R) + C_k(R)m^{-2/3} + \mathbf{E}_{\Omega_R} \max_{0 \leq \tau \leq T} \left| \int_0^\tau (\tilde{F}(I^{\nu,m}, \varphi^{\nu,m}) - \langle \tilde{F} \rangle^m(I^{\nu,m})) ds \right|.$$

Here  $\langle \tilde{F} \rangle^m$  stands for averaging of the function  $\mathbb{T}^m \ni I^m \mapsto \tilde{F}(I^m, 0, \dots)$ . So it remains to estimate for any  $m$  and  $R$  an analogy  $\mathfrak{A}_{m,R}^\nu$  of the quantity  $\mathfrak{A}^\nu$  for the finite-dimensional process  $I^{\nu,m}(\tau)$  on the event  $\Omega_R$  (where its norm is  $\leq R$ ),

$$\mathfrak{A}_{m,R}^\nu = \mathbf{E}_{\Omega_R} \max_{0 \leq \tau \leq T} \left| \int_0^\tau (\tilde{F}(I^{\nu,m}, \varphi^{\nu,m}) - \langle \tilde{F} \rangle^m(I^{\nu,m})) ds \right|.$$

Consider a partition of  $[0, T]$  by the points

$$\tau_j = \tau_0 + jL, \quad 0 \leq j \leq K,$$

where  $\tau_K$  is the last point  $\tau_j$  in  $[0, T]$ . The diameter  $L$  of the partition is

$$L = \sqrt{\nu},$$

and the non-random phase  $\tau_0 \in (0, L]$  will be chosen later. Denoting

$$\eta_l = \int_{\tau_l}^{\tau_{l+1}} (\tilde{F}(I^{\nu,m}, \varphi^{\nu,m}) - \langle \tilde{F} \rangle^m(I^{\nu,m})) ds, \quad 0 \leq l \leq K-1, \quad (2.16)$$

we see that

$$\mathfrak{A}_{m,R}^\nu \leq LC(R) + \mathbf{E}_{\Omega_R} \sum_{l=0}^{K-1} |\eta_l|, \quad (2.17)$$

so it remains to estimate  $\mathbf{E}_{\Omega_R} \sum |\eta_l|$ . We have

$$\begin{aligned} |\eta_l| &\leq \left| \int_{\tau_l}^{\tau_{l+1}} (\tilde{F}(I^{\nu,m}(s), \varphi^{\nu,m}(s)) - \tilde{F}(I^{\nu,m}(\tau_l), \varphi^{\nu,m}(\tau_l) + \nu^{-1}\Lambda^m(s - \tau_l))) ds \right| \\ &\quad + \left| \int_{\tau_l}^{\tau_{l+1}} (\tilde{F}(I^{\nu,m}(\tau_l), \varphi^{\nu,m}(\tau_l) + \nu^{-1}\Lambda^m(s - \tau_l)) - \langle \tilde{F} \rangle^m(I^{\nu,m}(\tau_l))) ds \right| \\ &\quad + \left| \int_{\tau_l}^{\tau_{l+1}} (\langle \tilde{F} \rangle^m(I^{\nu,m}(\tau_l)) - \langle \tilde{F} \rangle^m(I^{\nu,m}(s))) ds \right| =: \Upsilon_l^1 + \Upsilon_l^2 + \Upsilon_l^3. \end{aligned}$$

To estimate the quantities  $\Upsilon_l^j$  we first optimise the choice of the phase  $\tau_0$ . Consider the events  $\mathcal{E}_l, 1 \leq l \leq K$ ,

$$\mathcal{E}_l = \{I_k^\nu(\tau_l) \leq \gamma\}, \quad \text{where } \gamma \geq \nu^a, \quad a = 1/10. \quad (2.18)$$

By Lemma 2.1 and the Fubini theorem we can choose  $\tau_0 \in [0, L)$  in such a way that

$$K^{-1} \sum_{l=0}^{K-1} \mathbf{P}(\mathcal{E}_l) = \varkappa(\gamma^{-1}; R, m).$$

For any  $l$  consider the event

$$Q_l = \left\{ \sup_{\tau_l \leq \tau \leq \tau_{l+1}} |I^\nu(\tau) - I^\nu(\tau_l)|_{h_I} \geq P_1(R)L^{1/3} \right\},$$

where  $P_1(R)$  is a suitable polynomial. It is not hard to verify (cf. [KP08]) that  $\mathbf{P}(Q_l) \leq \varkappa_\infty(L^{-1})$ . Setting

$$\mathcal{F}_l = \mathcal{E}_l \cup Q_l$$

we have that

$$\frac{1}{K} \sum_{l=0}^{K-1} \mathbf{P}(\mathcal{F}_l) \leq \varkappa(\gamma^{-1}; R, m) + \varkappa(\nu^{-1/2}; m) =: \tilde{\varkappa}.$$

Accordingly,

$$\frac{1}{K} \sum_{l=0}^{K-1} |(\mathbf{E} - \mathbf{E}_{\mathcal{F}_l}) \Upsilon_l^j| \leq \frac{P(R)}{K} \sum_{l=0}^{K-1} \mathbf{P}(\mathcal{F}_l) \leq P(R) \tilde{\varkappa} := \tilde{\varkappa}_1, \quad j = 1, 2, 3.$$

Similar, since for  $\omega \notin \Omega_R$  the integrand in (2.16) is  $\leq Q(R)$ , then

$$\frac{1}{K} \sum_l |\mathbf{E}_{\Omega_R} \eta_l - \mathbf{E}_{\Omega_R \cup \mathcal{F}_l} \eta_l| \leq \tilde{\kappa} Q(R). \quad (2.19)$$

If  $\omega \notin \Omega_R \cup \mathcal{F}_l$ , then for  $\tau \in [\tau_l, \tau_{l+1}]$  we have that  $I_k^\nu(\tau_l) \geq \gamma - P_1(R)L^{1/3} \geq \frac{1}{2}\gamma$ , if  $\nu$  is small. This relation and (2.4), (2.5), (2.6) imply that

$$\mathbf{P}_{\Omega_R \cup \mathcal{F}_l} \{|\varphi^{\nu,m}(s) - (\varphi^{\nu,m}(\tau_l) + \nu^{-1}\Lambda^m(s - \tau_l))| \geq \nu^a \text{ for some } s \in [\tau_l, \tau_{l+1}]\} \leq \kappa^\infty(\nu^{-1}; R, m).$$

Accordingly,

$$\left( \sum_l \mathbf{E}_{\Omega_R \cup \mathcal{F}_l} \Upsilon_l^1 \right) \leq C\nu^a + \kappa^\infty(\nu^{-1}; R, m). \quad (2.20)$$

It is clear that

$$\left( \sum_l \mathbf{E}_{\Omega_R \cup \mathcal{F}_l} \Upsilon_l^3 \right) \leq P(R)L^{1/3} = P(R)\nu^{1/6}. \quad (2.21)$$

So it remains to estimate the expectation of  $\sum \Upsilon_l^2$ . For any  $\omega \notin \Omega_R \cup \mathcal{F}_l$  abbreviate

$$F(\psi) = \tilde{F}(I^{\nu,m}(t_l), \varphi^{\nu,m}(t_l) + \psi), \quad \psi \in \mathbb{T}^m,$$

where in the r.h.s.  $\psi$  is identified with the vector  $(\psi, 0, \dots) \in \mathbb{T}^\infty$ . We can write  $\Upsilon_l^2$  as

$$\Upsilon_l^2 = \left| \int_{\tau_l}^{\tau_{l+1}} F(\nu^{-1}\Lambda^m(s - \tau_l)) ds - \langle F \rangle \right| = L \left| \frac{\nu}{L} \int_0^{\nu^{-1}L} F(\Lambda^m t) dt - \langle F \rangle \right|.$$

Since the function  $F(\psi)$  is analytic and the vector  $\Lambda$  is non-resonant, then by Lemma 1.1  $\Upsilon_l^2 \leq L\kappa(\nu^{-1}L; m, R, \gamma, \Lambda)$ . Therefore

$$\left( \sum_l \mathbf{E}_{\Omega_R \cup \mathcal{F}_l} \Upsilon_l^2 \right) \leq \kappa(\nu^{-1/2}; m, R, \gamma, \Lambda). \quad (2.22)$$

Now (2.17), (2.19) and (2.20)- (2.22) imply that

$$\begin{aligned} \mathfrak{A}^\nu &\leq \kappa_\infty(R) + C(R)m^{-1/3} + \kappa(\nu^{-a}; R, m) + \kappa(\gamma^{-1}; R, m) \\ &\quad + C\nu^a + P(R)\nu^{1/6} + \kappa(\nu^{-1/2}; m, R, \gamma, \Lambda). \end{aligned}$$

Choosing first  $R$  large, then  $m$  large and next  $\gamma$  small and  $\nu$  small in such a way that (2.15) and (2.18) hold, we make the r.h.s. arbitrarily small. This proves the lemma.

## 2.4 Joint distribution of actions and angles.

Denote  $\tilde{\mu}_s^\nu = \mathcal{D}(I^\nu(s), \varphi^\nu(s)) = (I \times \varphi) \circ \mathcal{D}(u^\nu(s))$ , where  $u^\nu(s)$ ,  $0 \leq s \leq T$ , is a solution of (1.1) and  $(I^\nu, \varphi^\nu)$  is a solution of the system (2.3), (2.4). For any  $f \in L_1(0, T)$ ,  $f \geq 0$ , such that  $\int f = 1$ , set  $\tilde{\mu}^\nu(f) = \int_0^T f(s) \tilde{\mu}_s^\nu ds$ . Also let us denote  $m^0(f) = \int_0^T f(s) \mathcal{D}(I^0(s)) ds$ ; this is a measure on  $h_{I^+}$ .

**Theorem 2.4.** *For any  $f$  as above,*

$$\tilde{\mu}^{\nu_j}(f) \rightharpoonup m^0(f) \times d\varphi \quad \text{as } \nu_j \rightarrow 0. \quad (2.23)$$

*Proof.* For a piecewise constant function  $f$  the convergence follows from Theorem 2.2 and Lemma 2.3 since by the lemma, for any  $0 \leq T_1 < T_2 \leq T$ , the integral  $\int_{T_1}^{T_2} \tilde{F}(I^\nu(s), \varphi^\nu(s)) ds$  is close to  $\int_{T_1}^{T_2} \langle \tilde{F} \rangle(I^\nu(s)) ds$ , and by the theorem the integral  $\int_{T_1}^{T_2} \langle \tilde{F} \rangle(I^\nu(s)) ds$  is close to  $\int_{T_1}^{T_2} \langle \tilde{F} \rangle(I^0(s)) ds = \int_{\mathbb{T}^\infty} \int_{T_1}^{T_2} \tilde{F}(I^0(s), \psi) ds d\psi$  (we are applying the lemma and the theorem on segments  $[0, T_1]$  and  $[0, T_2]$ ).

To get the convergence for a general function  $f$  we approximate it by piecewise constant functions. See Section 2 of [Kuk10] for details.  $\square$ .

## 2.5 Multidimensional case.

Let (2.1) be not eq. (1.1), but eq. (1.14), written in the  $v$ -variables. Now we should consider (2.1) as an equation in a space  $h^r$ ,  $r > d/2$ . The maps  $P^1 : h^r \rightarrow h^r$  and  $P^2 : h^r \rightarrow h^r$  are smooth and the differentials  $d^m P^1(v) : h^r \times \cdots \times h^r \rightarrow h^r$  are poly-linear mappings such that their norms are bounded by polynomials of  $|v|_{h^r}$ . This allows to apply to eq. (2.1) the methods of [KP08]<sup>1</sup> in the same way as in Sections 2.3-2.4 and establish validity of Theorems 2.2 and 2.4.

## 3 Effective equations and uniqueness of limit.

Let (2.1) be eq. (1.1) or eq. (1.14), written in the  $v$ -variables, and (2.11) – the corresponding averaged equation. Accordingly, by  $h$  we denote either the space  $h^1$  as in Section 1, or the space  $h^r$ ,  $r > d/2$ , as in Section 1.3. For simplicity we assume that  $p$  and  $q$  in (1.14) are integers. If they are not, then in the calculations below the nonlinearities  $|u|^{2p}u$  and  $|u|^{2q}u$  should be modified by Lipschitz terms which cause no extra difficulties.

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<sup>1</sup>In was assumed in [KP08] that the relevant maps and vector-fields are analytic. This analyticity was imposed only for simplicity. Sufficiently high smoothness and polynomial estimates on the corresponding high order differentials are sufficient for all construction of [KP08].



### 3.1 Effective equations.

Let us write the averaged drift  $\langle v_k \cdot P_k \rangle$  and the averaged diffusion  $\langle A_{kr} \rangle$  in the form (2.8) and (2.9), respectively. Using (2.2) we write the term  $R'(v)$  in (2.8) as

$$R'_k(v) = \sum_{m=1}^3 \int e^{-i\theta_k} P_k^m(\Phi_\theta v) d\theta =: \sum_{m=1}^3 R_k^m(v), \quad k \geq 1.$$

By (1.22) and (1.23),

$$\begin{aligned} R^1(v) &= \varkappa \int \Phi_{-\theta} \Psi \left( \frac{\partial^2}{\partial x^2} G(\Phi_\theta v) \right) d\theta \\ &= -\varkappa \int \Phi_{-\theta} \hat{A} \Phi_\theta v d\theta + \varkappa \int \Phi_{-\theta} \mathcal{L}^0(\Phi_\theta v) d\theta \\ &= -\varkappa \hat{A} + \varkappa R^0(v), \quad R^0(v) = \int \Phi_{-\theta} \mathcal{L}^0(\Phi_\theta v) d\theta, \end{aligned} \tag{3.1}$$

since  $\hat{A}$  commutes with the rotations  $\Phi_\theta$ . The operator  $R^0$  is bounded and self-adjoint in  $h^0$ . For any  $v$  we have

$$\langle R^1(v), v \rangle = \varkappa \int \langle \Delta G \Phi_\theta v, G \Phi_\theta v \rangle d\theta \leq -C \varkappa |v|_{h^1}^2, \tag{3.2}$$

since  $\|G \Phi_\theta v\|_1 \sim |\Phi_\theta v|_{h^1} = |v|_{h^1}$ . Writing in (3.1)  $\mathcal{L}^0(v) = \Psi \circ V \circ G(v)$  as

$$\mathcal{L}^0(v) = \varkappa \nabla(h^2 \circ G)(v), \quad h^2(u) = \frac{1}{2} \int V(x) |u(x)|^2 dx,$$

we have  $R^0(v) = \nabla \langle h^2 \circ G \rangle(v)$ . Since

$$\begin{aligned} \langle h^2 \circ G \rangle(v) &= \frac{1}{2} \sum_{j,l} \int_{\mathbb{T}^\infty} \langle V(x) e^{i\theta_j} v_j \varphi_j(x), e^{i\theta_l} v_l \varphi_l(x) \rangle d\theta \\ &= \frac{1}{2} \sum_l |v_l|^2 M_l, \quad M_l = \langle V \varphi_l, \varphi_l \rangle, \end{aligned}$$

then  $R^0 = \text{diag}\{M_l, l \geq 1\}$ . Accordingly,

$$R^1 = \varkappa \text{diag}\{-\lambda_l + M_l, l \geq 1\} > 0, \quad M_l = \langle V \varphi_l, \varphi_l \rangle \tag{3.3}$$

The term  $R^2$  is defined as an integral with the integrand

$$\Phi_{-\theta} P^2 \Phi_\theta(v) = -\gamma_R \Phi_{-\theta} \Psi(|u|^{2p} u) \big|_{u=G \circ \Phi_\theta v} =: F_\theta(v).$$

Writing  $f^p(|u|^2)u^{-2}$  as  $\nabla h^p(u)$ , where  $h^p(u) = \int F^p(|u|^2) dx$ ,  $(F^p)' = \frac{1}{2}f^p$ , and denoting  $G \circ \Phi_\theta = L_\theta$ , we have

$$F_\theta(v) = -\gamma_R L_\theta^* \nabla h^p(u) \big|_{u=L_\theta(v)} = -\gamma_R \nabla(h^p \circ L_\theta(v)).$$

So

$$R^2(v) = -\gamma_R \nabla_v \left( \int_{\mathbb{T}^\infty} (h^p \circ G)(\Phi_\theta v) d\theta \right) = \gamma_R \nabla_v \langle h^p \circ G \rangle. \quad (3.4)$$

Similar  $R^3(v) = -i\gamma_I \nabla_v \langle h^q \circ G \rangle$  (since the operator  $G \circ \Phi_\theta$  is complex-linear). As  $\langle h^q \circ G \rangle$  is a function solely of the actions  $(I_1, I_2, \dots)$ , then  $\nabla_{v_k} \langle h^q \circ G \rangle \in \mathbb{C}$  is a vector, real-proportional to  $v_k$ . Therefore  $v_k \cdot R_k^3(v) = 0$  for each  $k$ . That is,

$$\langle (v_k \cdot P_k) \rangle(v) = v_k \cdot R_k^1(v) + v_k \cdot R_k^2(v), \quad (3.5)$$

where  $R^1$  and  $R^2$  are defined by (3.3) and (3.4). Now we set

$$R(v) = R^1(v) + R^2(v)$$

and consider the following system of stochastic equations:

$$dv_k(\tau) = R_k(v) d\tau + Y_k d\beta_k, \quad k \geq 1. \quad (3.6)$$

Equations (3.6) are called the *system of effective equations*.

*Example 3.1.* ( $p = 1$ ). Now  $h^1(u) = \frac{1}{4} \int |u|^4 dx$ . So

$$h^1 \circ G(v) = \frac{1}{4} \int \left| \sum_k v_k \varphi_k(x) \right|^4 dx = \frac{1}{4} \sum_{k_1, k_2, k_3, k_4} v_{k_1} v_{k_2} \bar{v}_{k_3} \bar{v}_{k_4} \int \varphi_{k_1} \varphi_{k_2} \varphi_{k_3} \varphi_{k_4} dx.$$

Since

$$\langle v_{k_1} v_{k_2} \bar{v}_{k_3} \bar{v}_{k_4} \rangle = \begin{cases} |v_{k_1}|^2 |v_{k_2}|^2 & \text{if } k_1 = k_3, k_2 = k_4 \text{ or } k_1 = k_4, k_2 = k_3, \\ 0 & \text{otherwise,} \end{cases}$$

then

$$\langle h^1 \circ G(v) \rangle = \frac{1}{2} \sum_{k_1 \neq k_2} |v_{k_1}|^2 |v_{k_2}|^2 L'_{k_1 k_2} + \frac{1}{4} \sum_k |v_k|^4 L'_{kk}, \quad (3.7)$$

---

<sup>2</sup>if  $d = 1$  and  $p$  is an integer, than  $f^p(|u|^2) = |u|^{2p}$ .

where  $L'_{k_1 k_2} = \int \varphi_{k_1}^2 \varphi_{k_2}^2 dx$ . So that

$$\begin{aligned} R_k^2(v) &= -\gamma_R \nabla_{v_k} \langle h^1 \circ G \rangle(v) = -\gamma_R v_k \left( |v_k|^2 L'_{kk} + 2 \sum_{l \neq k} |v_l|^2 L'_{kl} \right) \\ &= -\gamma_R v_k \sum_l |v_l|^2 L_{kl}. \end{aligned}$$

Here  $L_{kk} = L'_{kk}$  and  $L_{kl} = 2L'_{kl}$  if  $k \neq l$ . So the system of effective equations becomes

$$dv_k = -v_k \left( \varkappa(\lambda_k - M_k) + \gamma_R \sum_l |v_l|^2 L_{kl} \right) d\tau + Y_k d\beta_k, \quad k \geq 1. \quad (3.8)$$

□

If  $v(\tau) = \{v_k(\tau), k \geq 1\}$  satisfies (3.6), then for  $I_k = I(v_k(\tau))$  we have

$$dI_k(\tau) = v_k \cdot R_k(v) d\tau + Y_k^2 d\tau + Y_k v_k \cdot d\beta_k, \quad k \geq 1. \quad (3.9)$$

By (3.5) the drift in this system equals  $(\langle v_k \cdot P_k \rangle(I) + Y_k^2) d\tau$ , while the diffusion matrix is  $\delta_{kr} |v_k|^2 Y_k^2 = \langle A_{kr} \rangle$ . So system (3.9) has the same set of weak (= martingale) solutions as (2.11), see [Yor74]. We have got

**Proposition 3.2.** *Let  $v(\tau)$  be a weak solution of (3.6) such that  $v(0) = v_0$  and*

$$\mathbf{E} \sup_{0 \leq \tau \leq T} |v(\tau)|_h^{2n} \leq C |v_0|_h^{2n} + C(n, T), \quad \forall n. \quad (3.10)$$

*Then  $\Pi_I(v(\tau))$  is a weak solution of the system (2.11), satisfying (2.12) and such that  $I(0) = I_0$ .*

That is, the solutions of eq. (2.11) which can be obtained as limits (when  $\nu \rightarrow 0$ ) of actions  $I^\nu(u(\tau))$  of solutions for (1.1) (or (1.14)) are those which can be covered by “regular” solutions of (3.6).

The ‘right’ inverse statement to Proposition 3.2 is given by the following

**Proposition 3.3.** *Let  $I^0(\tau)$  be a weak solution of the averaged equations (2.11), constructed in Theorem 2.2. Then there exists a weak solution  $v^0(\tau)$  of (3.6) such that  $v(0) = v_0$ , satisfying (3.10), and such that  $\mathcal{D}(\Pi_I(v^0(\cdot))) = \mathcal{D}(I^0(\cdot))$ .*

For a proof we refer to Section 3 of [Kuk10], where the assertion is established in a similar but more complicated situation.

System (3.6) is invariant under rotations  $\Phi_\theta$ :

**Proposition 3.4.** *Let  $v(\tau)$  be a weak solution of (3.6), satisfying (3.10). Then, for any  $\theta \in \mathbb{T}^\infty$ ,  $\Phi_\theta v(\tau)$  is a weak solution of (3.6), satisfying (3.10).*

*Proof.* Applying  $\Phi_\theta$  to (3.6) we get that

$$d(\Phi_\theta v) = \Phi_\theta R(v) d\tau + \Phi_\theta Y d\beta(\tau), \quad Y = \text{diag}\{Y_k\}.$$

The vector fields  $R^1(v)$  and  $R^2(v)$  both are obtained by averaging and have the form  $R^j(v) = \int \Phi_{-\theta} F^j(\Phi_\theta v) d\theta$ . So they commute with the rotations, as well as their sum  $R(v)$ , and we have

$$d(\Phi_\theta v) = R(\Phi_\theta v) d\theta + Y d(\Phi_\theta \beta(\tau)).$$

Since  $\mathcal{D}\Phi_\theta \beta(\tau) = \mathcal{D}\beta(\tau)$ , then the assertion follows.  $\square$

### 3.2 The uniqueness.

Let  $v^1(\tau)$  and  $v^2(\tau)$  be solutions of the effective system (3.6). Denoting  $v = v^1 - v^2$ , we have that

$$\frac{1}{2} \frac{d}{d\tau} |v(\tau)|_{h^0}^2 \leq -\kappa |v|_{h^1}^2 + \langle R^2(v^1) - R^2(v^2), v^1 - v^2 \rangle.$$

Consider the last term, denoting  $v_\theta^j = \Phi_\theta v^j$ ,  $u_\theta^j = G(v_\theta^j)$ . Since  $R^2(v)$  is an integral over  $\mathbb{T}^\infty$  with the integrand  $-\gamma_R \Phi_{-\theta} \Psi(|u_\theta|^{2p} u_\theta)$ , where  $u_\theta = G(\Phi_\theta(v))$ , then

$$\begin{aligned} \langle R^2(v^1) - R^2(v^2), v^1 - v^2 \rangle &= -\gamma_R \int \langle \Psi(|u_\theta^1|^{2p} u_\theta^1 - |u_\theta^2|^{2p} u_\theta^2), \Phi_\theta v^1 - \Phi_\theta v^2 \rangle d\theta \\ &= -\gamma_R \int \langle (|u_\theta^1|^{2p} u_\theta^1 - |u_\theta^2|^{2p} u_\theta^2), u_\theta^1 - u_\theta^2 \rangle d\theta. \end{aligned}$$

The integrand in the r.h.s. is non-negative. So

$$\frac{1}{2} \frac{d}{d\tau} |v|_{h^0}^2 \leq -C\kappa |v|_{h^1}^2, \tag{3.11}$$

(i.e., the effective system (3.6) is strongly monotone). Therefore a strong solution of the system (3.6) is unique. By the Yamada-Watanabe argument (see [KS91]) a weak solution also is unique. We have got

**Theorem 3.5.** *Let  $I^\nu(\tau) = I(u^\nu(\tau))$ , where  $u^\nu(\tau)$  is a solution of eq. (1.1) or of eq. (1.14) and  $u^\nu(0) = u_0$ . Then*

$$\mathcal{D}(I^\nu(\cdot)) \rightharpoonup Q^0 \quad \text{as } \nu \rightarrow 0$$

*in the space  $\mathcal{H}_I$ , where  $Q^0$  is a weak solution of (2.11), satisfying (2.12), (2.13). There exists a unique weak solution  $v(\tau)$  of the effective equations (3.6), satisfying (3.10), such that  $v(0) = \Psi(u_0)$  and  $\mathcal{D}(\Pi_I(v(\cdot))) = Q^0$ .*

## 4 Stationary solutions.

### 4.1 Averaging.

Again, let (2.1) be eq. (1.1) or eq. (1.14), written in the  $v$ -variables, and (2.11) be the corresponding averaged equation. Accordingly, by  $h$  we denote either the space  $h^1$  as in Section 1, or the space  $h^r$ ,  $r > d/2$ , as in Section 1.3. Assume that the corresponding  $u$ -equation is regular in the space  $\mathcal{H}^r$  (e.g.,  $d = 1$  or the assumptions, given at the end of the Section 1.3 are fulfilled), and that it has a unique stationary measure  $\mu^\nu$  (see Sections 1.2, 1.3).

Let  $u''^\nu(\tau)$  be a stationary in time solution of equation (1.1),  $\mathcal{D}(u''^\nu(\tau)) \equiv \mu^\nu$ . By estimates in Section 1 the set of laws  $\mathcal{D}(I''^\nu(\cdot))$ , where  $I''^\nu = I(u''^\nu(\tau))$ , is compact in  $h_I$ . Let  $Q'$  be any limiting measure as  $\nu_j \rightarrow 0$ . Clearly it is stationary in  $\tau$ . The same argument that was used to prove Theorem 2.2 (cf. [KP08]) imply that  $Q'$  is a stationary solution of the averaged equation:

**Proposition 4.1.** *The measure  $Q'$  is the law of a process  $I'(\tau)$ ,  $0 \leq \tau \leq T$ , which is a stationary weak solution of the averaged equation (2.11). It satisfies estimates (2.12), (2.13), and the stationary measure  $\pi = \mathcal{D}(I'(0))$  meets estimates (1.11), (1.12) with  $\nu = 0$ .*

The measures  $(I \times \varphi) \circ \mu^\nu = \mathcal{D}(I''^\nu(s), \varphi''^\nu(s))$  satisfies (2.23) for the same reason as in Section 2.4. Since the measure  $\mu^\nu$  is independent from  $s$ , then now

$$\mathcal{D}(I''^\nu(s), \varphi''^\nu(s)) \rightharpoonup \pi \times d\varphi \quad \text{as } \nu_j \rightarrow 0. \quad (4.1)$$

In the stationary case relation (2.7) implies that

$$\mathbf{P}\{I''^\nu_k(\tau) < \delta\} \rightarrow 0 \quad \text{as } \delta \rightarrow 0, \quad (4.2)$$

uniformly in  $\nu$ . In particular,

$$\pi\{I \mid I_k = 0\} = 0 \quad \forall k. \quad (4.3)$$

## 4.2 Lifting to effective equations.

To study the limiting measure  $\pi$  further we lift it to a stationary measure of the effective system (3.6). We start with

**Lemma 4.2.** *Assume (1.10). Then the system (3.6) has a unique stationary measure  $m$ .*

*Proof.* Relation (1.10) implies that  $Y_k \neq 0$  for all  $k$ . That is, the noise in the effective equations is non-degenerate. Moreover, the coefficients  $Y_k$  satisfy (2.10). Since solutions of (3.6) satisfy estimates (3.10) and since any two solutions converge by (3.8), then the assertion follows. E.g., see [KS10], Section 3.  $\square$

Let  $v(\tau)$  be a stationary solution of (3.6),  $\mathcal{D}(v(\tau)) \equiv m$ . By Proposition 3.4,  $\Phi_\theta(v(\tau))$  also is a (weak) stationary solution. So  $\mathcal{D}(\Phi_\theta v(\tau)) = \Phi_\theta \circ m$  is a stationary measure for (3.6). Since it is unique, then

$$\Phi_\theta \circ m = m \quad \forall \theta \in \mathbb{T}^\infty.$$

Accordingly,  $\Pi_\varphi \circ m$  is a rotation-invariant measure on  $\mathbb{T}^\infty$ , i.e.  $\Pi_\varphi \circ m = d\varphi$ . This implies that in the  $(I, \varphi)$ -variables the measure  $m$  has the form

$$dm = m_I(dI) \times d\varphi \tag{4.4}$$

Proposition 4.1 applies for any time-interval  $[0, T]$ . So, replacing the sequence  $\nu_j \rightarrow 0$  by a suitable subsequence  $\nu_{j'} \rightarrow 0$  we construct a stationary process  $I'(\tau)$ ,  $\tau \geq 0$ , such that  $I'^{\nu_{j'}}(\tau)$  converges to  $I'(\tau)$  in distribution on any finite time-interval. Using Theorem 3.4 and discussion at the end of Section 3.1 we construct a solution  $v'(\tau)$  of (3.6) such that  $\mathcal{D}(\Pi_I(v'(\tau))) \equiv \pi$ . Since  $\mathcal{D}(v'(\tau)) \rightarrow m$  as  $\tau \rightarrow \infty$ , then

$$\pi = \Pi_I \circ m. \tag{4.5}$$

That is, the measure  $\pi$  is independent from the sequence  $\nu_j$ . We have got

**Theorem 4.3.** *If (1.10) holds, then  $I \circ \mu^\nu \rightarrow \pi = \Pi_I \circ m$ , where  $m$  is the unique stationary measure of the effective system.*

In view of (4.1), (4.4) and (4.5),

$$(I \times \varphi) \circ \mu^\nu \rightarrow (\Pi_I \times \Pi_\varphi) \circ m \quad \text{as } \nu \rightarrow 0.$$

Denote  $h_+ = \{v \in h \mid v_j \neq 0 \ \forall j\}$ . By (4.2) and (4.3)  $(\Psi \circ \mu^\nu)(h_+) = 1$  and  $m(h_+) = 1$ . So the convergence above implies that

**Theorem 4.4.** *If (1.10) holds, then  $\mu^\nu \rightharpoonup G \circ m$  as  $\nu \rightarrow 0$ .*

*Example 4.5.* (Hamiltonian perturbations.) If in (1.14)  $\gamma_R = 0$ , i.e. if the non-linear term of the perturbation is Hamiltonian, then the effective system is the linear equation

$$dv(\tau) = R^1(v) d\tau + Y d\beta,$$

where  $R^1$  is defined in (3.3) and  $Y = \text{diag}\{Y_k, k \geq 1\}$ . Let  $v(0) = 0$ . Then  $v(\tau)$  is the diagonal complex Gaussian process

$$v(\tau) = \int_0^\tau e^{(\tau-s)R^1} Y d\beta(s), \quad R^1 = \kappa(\hat{A} - R^0).$$

So the stationary measure for the effective system,  $\mathcal{D}v(\infty)$ , is a direct sum of independent complex Gaussian measures with zero mean and the dispersions  $\kappa^{-1}Y_k^2/(\lambda_k - M_k)$ ,  $k \geq 1$ .

The fact that a Hamiltonian nonlinearity produces no effect in the first order averaging (i.e. for the slow time  $\tau \lesssim 1$ ) is well known in the theory of weak turbulence. To produce a non-trivial effect, the Hamiltonian term  $-i\gamma_I f_q(|u|^2)u$  should be scaled by the additional factor  $\nu^{-1/2}$ , and for the weak turbulence theory to apply to calculate this effect we should send the size of the  $x$ -torus to infinity when  $\nu \rightarrow 0$ , see [Naz11].

*Example 4.6.* ( $p = 1$ , continuation). If  $p = 1$ , then the effective equations become

$$dv_k = -v_k(\kappa(\lambda_k - M_k) + \gamma_R \sum_l |v_l|^2 L_{kl}) d\tau + Y_k d\beta_k. \quad (4.6)$$

Assume that the random force in (1.1) (or in (1.14)) is small and is mostly concentrated at a frequency  $j_*$ . That is,

$$b_{j_*} = \varepsilon < 1, \quad 0 < b_l \ll \varepsilon \quad \text{if } l \neq j_*.$$

Then the numbers  $Y_k$  are of order  $\varepsilon$  and are concentrated close to  $j_*$ , i.e.,

$$Y_{j_*} \sim \varepsilon, \quad Y_l \leq \varepsilon C_N |l - j_*|^{-N} \quad \forall l, N.$$

So if  $v(\tau)$  is a stationary solution of the effective equations and  $E_k = \frac{1}{2} \mathbf{E}|v_k(\tau)|^2$ , then

$$E_{j_*} \sim \varepsilon^2 \lambda_{j_*}^{-1}, \quad E_l \leq \varepsilon^2 C_N \lambda_{j_*}^{-1} |l - j_*|^{-N} \quad \forall l, N.$$

That is, the systems (1.1) and (1.14) exhibit no inverse or direct cascade of energy. For other polynomial systems (1.1) and (1.14) situation is the same. Certainly this is not surprising since by imposing the non-resonance condition we removed from the system resonances, responsible for the two energy cascades.

## 5 Equations with non-viscous damping.

Following Debussche-Odasso [DO05] we now discuss equations (1.1) with non-viscous damping, i.e. with  $\varkappa = 0$  but with  $\gamma_R > 0$  and  $p = 0$  (Debussche-Odasso considered the case  $p = 0, q = 1$ ):

$$\begin{aligned} \dot{u} + i\nu^{-1}(-u_{xx} + V(x)u) &= -\gamma_R u - i\gamma_I |u|^{2q} u + \frac{d}{d\tau} \sum b_j \beta_j(\tau) e_j(x), \\ u(x) &\equiv u(x + 2\pi) \equiv -u(-x); \end{aligned} \quad (5.1)$$

$$u(0) = u_0. \quad (5.2)$$

Estimates (1.4), (1.8) and (1.9) are valid with  $\varkappa = 0$ . Jointly with an analogy of estimate (1.17) with  $\varkappa = 0, m = 1$  they imply that for  $u_0 \in \mathcal{H}^2$  the set of actions  $I^\nu(\tau) = I(u^\nu(\tau))$  of solutions for (5.1), (5.2) is tight in  $\mathcal{H}_I$ . As in Section 2, any limiting measure  $Q^0 = \lim \mathcal{D}(I^{\nu_j}(\cdot))$  is a law of a weak solution  $I^0(\tau)$  of the averaged equations (2.11) $_{\varkappa=0}$  with  $I(0) = I_0 = I(u_0)$ . Constructions of Section 3 remain true, so  $I^0(\tau)$  may be lifted to a weak solution  $v^0(\tau)$  of the effective equations (3.6) $_{\varkappa=0, p=0}$ . Now  $R^1 = 0$  and, repeating constructions of Example 3.1 we see that  $R_k^2(v) = -\gamma_R v_k$ . So the effective equations become the linear system

$$dv_k(\tau) = -\gamma_R v_k d\tau + Y_k d\beta_k. \quad (5.3)$$

This system has a unique solution  $v(\tau)$  such that  $v(0) = v_0 = \Psi(u_0)$ . So

$$\lim_{\nu \rightarrow 0} \mathcal{D}(I^\nu(\cdot)) = \mathcal{D}\Pi_I(v(\cdot)).$$

Due to results of [DO05], eq. (5.1) has a unique stationary measure  $\mu^\nu$ . Repeating arguments from Example 4.5, we see that when  $\nu \rightarrow 0$ , the measures  $\Psi \circ \mu^\nu$  converge to the unique stationary measure of eq. (5.3) which is

$$m = \mathcal{D} \int_{-\infty}^0 \text{diag}\{e^{-s\gamma_R} Y_k\} d\beta_k(s).$$

This is a direct sum of independent complex gaussian measures with zero mean and the dispersion  $Y_k^2/\gamma_R$ ,  $k \geq 1$ . So every solution  $u(\tau)$  of (5.1) satisfies the Gaussian limit

$$\lim_{\nu \rightarrow 0} \lim_{\tau \rightarrow \infty} \mathcal{D}u(\tau) = G \circ m.$$

If we replace in (5.1) the linear damping by the nonlinear term  $-\gamma_R |u|^2 u$ , then the effective system (5.3) should be replaced by the nonlinear system (4.6) with  $\lambda_k = M_k = 0$ . In this case the limiting measure is non-Gaussian.



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